PERGAMON

Renewable and Sustainable Energy Reviews
2 (1998) 89–114

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

Chapter 5—The utilization of microclimate elements

Cettina Gallo*

E.N.E.A., Casella Postale N. 2358, 00100 Roma A.D., Italy

1. Introduction

In architectural design the knowledge of microclimate elements is important: wind and local breezes, sun and shadows, humidity and vegetation, etc if well utilised, can strongly contribute to the thermal well-being of the inhabitants. If these elements are manipulated by the creativity of the architect they often inspire new architectural shapes: therefore an accurate knowledge of local climate factors and of the thermal characteristics of construction materials must be part and parcel of the architect's background information and a source of inspiration in the creative process.

2. The wind

Wind is an important element in the design of a bioclimatic house: two typical elements of the oriental architecture, the wind-towers and the 'malqaf' are significant examples. Wind towers, originated in Iran around the 10th Century, and are also called 'baud geers' (the Persian word means literally 'wind catcher'). A wind tower is made by a kind of large chimney vertically slit in its upper part by several brick baffles. During night time the tower cools off; the air coming in contact with the tower also cools off, becomes heavier and descends the interior of the tower, thereby penetrating the building. On windy days this process is further enhanced. The air enters the side of the tower exposed to the wind, descends and goes through the building, exiting from the doors that face the central hall and the basement. The pressure created by the cool air pushes hot air out of the building through doors and windows.

During day time the tower absorbs heat, which is then transmitted to the air at night, thereby creating an uplift current; when there is need for further cooling, this current can be employed to suck in the building the fresh air of the night. When the night is windy, the air flows down the side of the tower which is exposed to the wind

* Corresponding author. Tel.: +0039-6-3627-2243

PII: S1364–0321(98)00013–6

and is warmed by the contact with the masonry, while an upward current is generated in the leeward section of the tower. By appropriate opening or closing of the various sections of the tower and/or of the building, the tower will cool off different sections of the building as needed. Wind towers are often used in conjunction with curved roofs or domes, which constitute other elements of environmental comfort during the summer heat.

In fact, hot air tends to raise to the vault above the living area; furthermore, while a curved roof receives the same amount of radiation as a flat roof of comparable area, the former offers a greater surface to transfer heat (by radiation and convection) to the exterior during night time. A round hole placed in the upper section of the dome further improves the circulation of the air. When it is windy the passage of the air above the external curved surface of the dome causes a point of depression at the apex of the dome. This depression sucks away the hot air which accumulated on the interior of the dome. The eyelet at the peak of the dome is usually covered by a cap pierced by several small openings which deflect the wind and increase the suction of the hot air. Usually the opening on the vault is placed over the living area. Sometimes domes are used in conjunction with wind towers; other times, especially when the wind carries a lot of sand, the domes are used without wind towers. Often, in areas where the winds blow most of the time in the same direction, the dome is substituted by a barrel vault whose longitudinal axis is perpendicular to the wind.

The most efficient natural cooling systems found in traditional Iranian architecture make use of water. These systems exploit the cooling effect caused by the evaporation of water. Warm air when blown over a water surface, or a damp wall, transfers part of its heat to the water, causing a partial evaporation. This cooling effect is achieved by the Iranians through various means; sometimes they use the natural dampness of the underground portion of the wind tower, or of the underground ducts connecting the tower to the house. These underground ducts were traditionally used for food conservation before the coming of modern refrigerators. A water basin and a fountain placed in the basement of the wind tower or in the room connected to the duct coming from the tower can supply further cooling by evaporation. In other cases, the air coming from the wind tower at a high velocity sucks the cool and damp air from these. A particularly efficient water cooling system uses a combination of several wind towers (four or more) and a cistern. This cistern is dug into the ground to a depth varying from 10–20 m. It is then covered by a dome surrounded by several wind towers. This system utilizes the seasonal temperature variations of the desert area, and also the insulating characteristic of the ground, which maintains a constant temperature throughout the year. The cistern is partially filled with cold water in winter. In summer time the constant air current created by the wind towers carries away the surface layer of the water, after its evaporation. In this way the external heat cannot penetrate the lower levels of the reservoir, and large amounts of water remain cool during the whole summer, even in the middle of the desert.

To satisfy the need for ventilation alone, the ‘malqaf’, or wind-catch, was invented. This device dates back to very early historical times: it is represented in Egyptian wall paintings of the tombs of Thebes, which date from the Nineteenth Dynasty (1300 B.C.). The malqaf is a shaft rising high above the building with an opening facing the

prevailing wind. It traps the wind from high above the building where it is cooler and stronger, and channels it down into the interior of the building. The size of the malqaf is determined by the external air temperature. A large size is required where the air temperature at the intake is low, and a smaller size where the ambient air temperature is higher than the limit for thermal comfort, provided that the air flowing through the malqaf is cooled before it is allowed to circulate into the interior.

In some designs, the drafts from the malqaf outlet are cooled by passing over water in the basement. However this method is not very effective, and some other device is required to provide air cooling, at increased rates of airflow, sufficient to meet the conditions of both hygiene and thermal comfort. By increasing the size of the malqaf and suspending wetted matting in its interior, the airflow rate can be increased while providing effective cooling. People in Iraq hang wet mats outside their windows to cool the wind flowing into the room by evaporation. The matting can be replaced by panels of wet charcoal held between sheets of chicken wire. Evaporation can be further accelerated by employing the Bernoulli effect or Venturi action with baffles of charcoal panels placed inside the malqaf. The wind blowing down through the malqaf will decrease the air pressure below the baffle, which increases airflow and thus accelerates evaporation. Metal trays holding wet charcoal can be advantageously used as baffles. Air can be directed over a salsabil, a fountain or a basin of still water, to increase air humidity. The baffles are also effective in filtering dust and sand from the wind.

The malqaf is still today incorporated into new architectural designs. The value of the malqaf is even more obvious in dense cities in warm humid climates, where thermal comfort depends mostly on air movement. Since massive buildings reduce the wind velocity at street level and screen each other from the wind, ordinary windows are inadequate for ventilation. This situation can be corrected by using the malqaf. Actually, a great advantage of both the malqaf and the wind tower is that they solve the problem of screening resulting from the blocking of buildings in an ordinary town plan. Several research centers have been working to develop the best configuration for locating blocks of buildings, while avoiding screening of blocks by those upwind; but after six or seven blocks no configuration will solve the problem of screening. The malqaf and the wind tower, however, being smaller in size than the buildings themselves, do provide an effective solution.

Another example of cold air utilisation in buildings comes from Italy: a group of six villas built in the 16th century near Vicenza was equipped with a remarkable system of underground air conduits that provided air-conditioning during the hot Mediterranean summer. The system includes natural cavities and manmade passages tunnelled through the hill on which the villas stand. The temperature of the air in the cavities is practically constant at 11–12°C all year round. During the summer, when the outdoor air is hotter than the air underground, a natural circulation system is created. Hot outdoor air is drawn into the underground cavities and flows out, now cool, into the cellars of the villas and thence into the rooms above through adjustable stone or marble grates set in the floor.

In the same century the work of Raphael, the Italian painter and architect, indicates that this Master was well aware of bioclimatic issues and of the main winds of the

local microclimate. In one of his letters, Raphael describes the Villa Madama, just commissioned by Pope Alexander VII, in bioclimatic terms. The terms 'sirocco' (the south-east of the sea wind from that direction) and 'libeccio' (south-western wind), are used not only to explain the orientation of the rooms, but also to show how the layout of the rooms was coherent with the external climatic influences. This letter puts into evidence the sound knowledge Raphael had of the bioclimatic question, and the care he gave to environmental comfort. Raphael writes

> "... In order to expose the villa (Madama) to healthier winds, I have oriented it lengthwise Sirocco and Mistral (north-west wind), taking care not to have any of the living area windows facing Sirocco, but only those windows that need heat" [1].

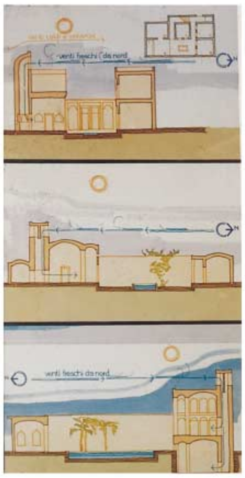
In the exedre of the Villa Madama (Rome) the windows are oriented by 15°C east in respect to the east-west solar axis, in consideration of the asymmetrical course of the sun in respect to the hours of the day. The exedre windows so designed would have looked somewhat incomplete (while correct from a solar point of view) out of balance in respect to the final arch. Raphael therefore built two blank windows with the purpose of protecting the eastern windows from the uncomfortable western sun. But when the wind is not a strong element of microclimate, it has to be created for a passive cooling in architecture. It is important for an architect to know how airflows can be developed; the Egyptian master Hassan Fathy wrote:

> "Another science to which architecture is indebted is aerodynamics. The methods of investigating airflow around the wings and bodies of aircraft are now being used to study airflow through, over, and around buildings. Scaled and full-size models can be tested in wind tunnels to determine the effect of the size, location, and arrangement of openings on the airflow through individual buildings, as well as the nature of wind patterns and forces between groups of buildings" [2].

The French architect Laszlo Mester de Paraijd utilises very well the airflows in the plans and sections of his buildings in Africa to give physiological well-being and cool; slanted and ventilated counterwalls are used extensively in the Arlit and Agadez courthouse and the Court of Appeals building in Niamey (see Figure). He writes:

> "When air can circulate freely between a cool open space and a hot open space, a natural flow is created from the colder to the warmer space. Based on this principle, natural cold-air flows were created to cool the various parts of the building, circulating from one inner courtyard to another and from the courtyards to the outdoors, according to the amount of sunlight and the kind of ground covering" [3].

At the Faculty of Philosophy of the University of Iannina in Greece, a row of PVC pipes of 25 cm in diameter have been laid at 1.5 m under ground level. Their purpose is to precool the air entering the building during the summer before it flows to the University libraries. The same system has also been experimented in an agricultural



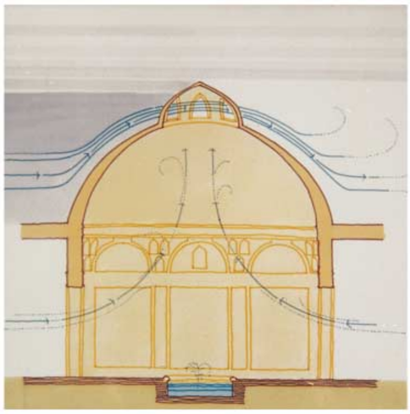
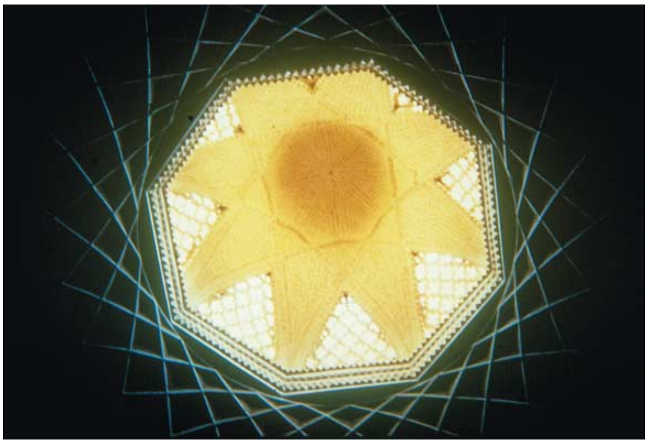


Fig. 1 (top left). Yazd (Iran)—Tower of the wind. Fig. 2 (top centre). Section of a tower of the wind. Fig. 3 (top right). Tower of the wind. Fig. 4 (middle left). Sections of the tower of the wind. Fig. 5 (middle right). Yazd (Iran).Fig. 6 (right). Yazd (Iran).



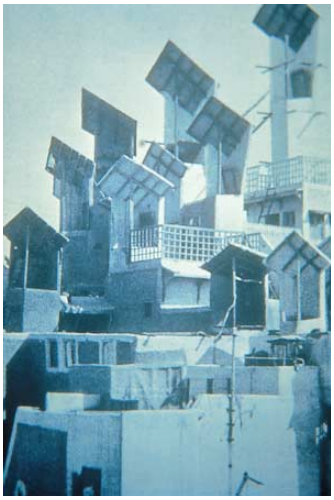
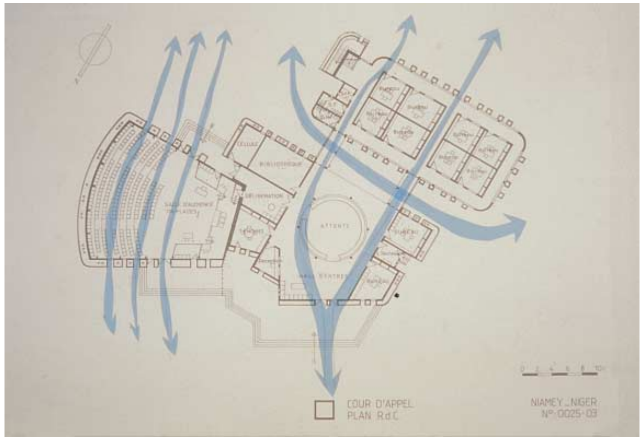
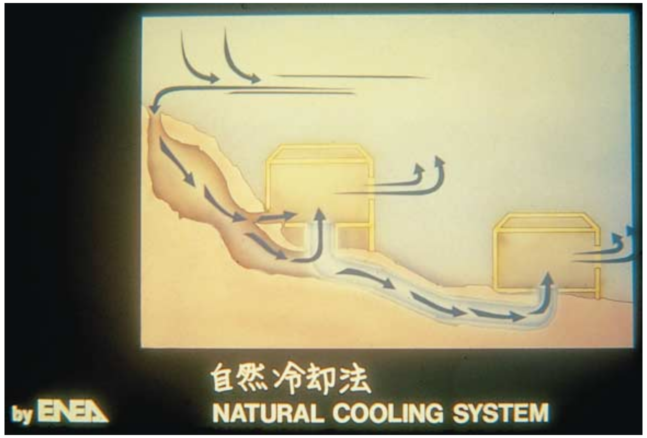


Fig. 7 (top). Yazd (Iran). Fig. 8 (middle left). Sind (Pakistan): malqaf. Fig. 9 (middle right). 'Mit Rehan', Shabramant, Egypt (1980), qa'a dome and chimneys. Fig. 11. L. Mester de Parajid, Cour d'Appel Niamey (Niger).





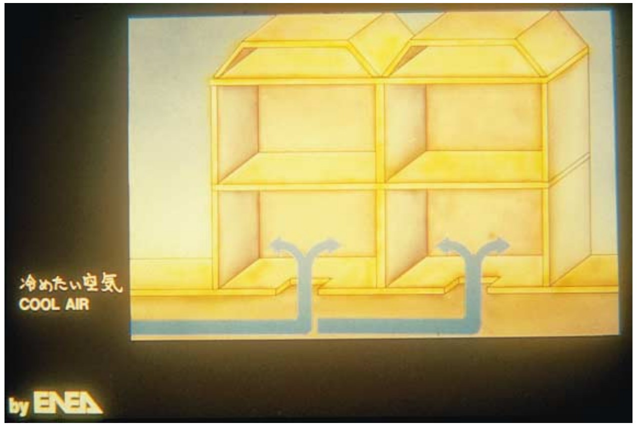
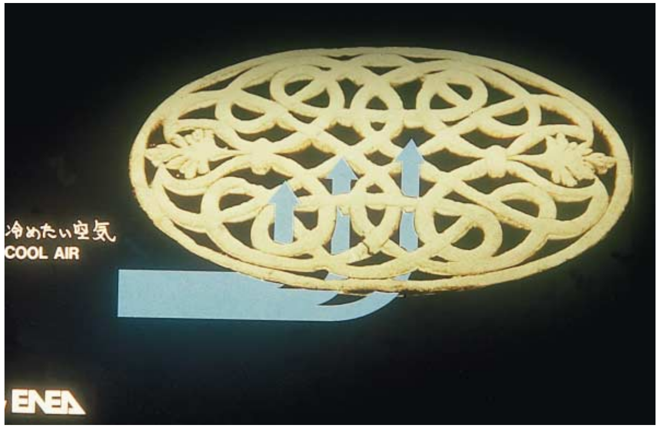


Fig. 12 (top left). L. Mester de Parajid, Cour d'Appel Niamey (Niger). Fig. 13 (top right). The Villas of Costozza, Italy. Fig. 14 (left). The Villas of Costozza, Italy. Fig. 15 (right). The Villas of Costozza, Italy.



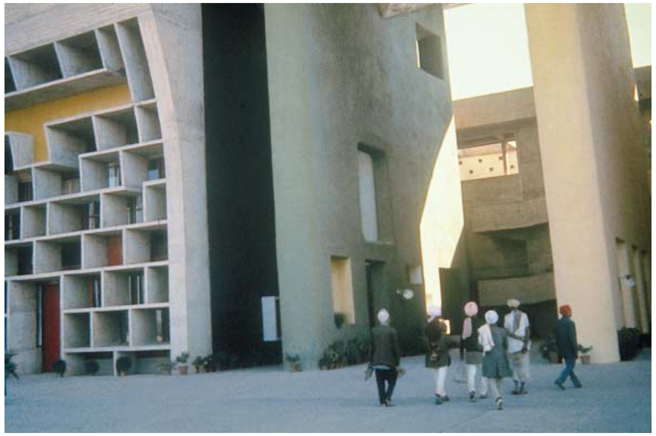
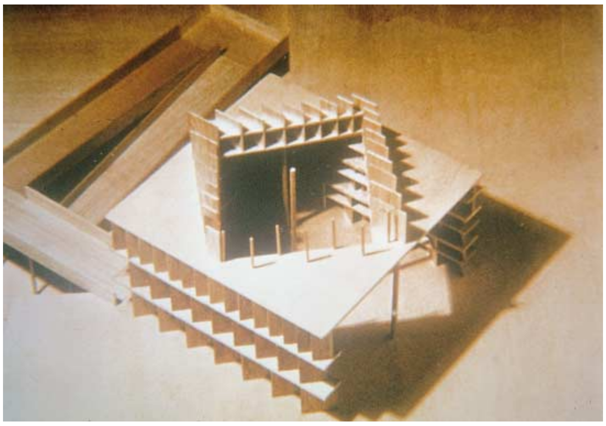


Fig. 16 (top left). The Villas of Costozza, Italy. Fig. 17 (top right). Villa Madama of Raphael, Rome, Italy. Fig. 20 (left). Le Corbusier—Monastery of 'La Tourette', L'Arbesle (Lyon), France. Fig. 21 (right). Le Corbusier—Buildings in Chandigar (India).



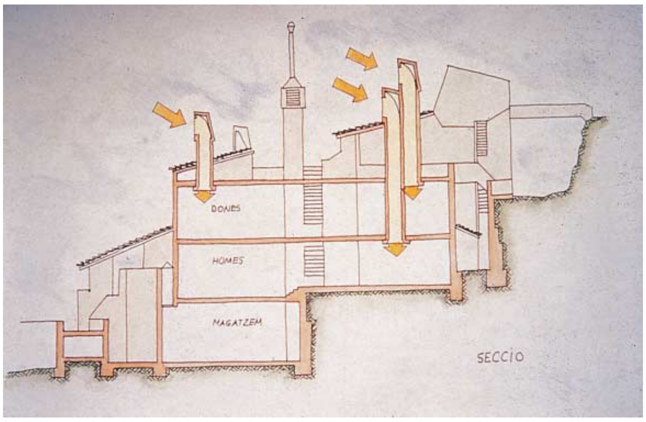
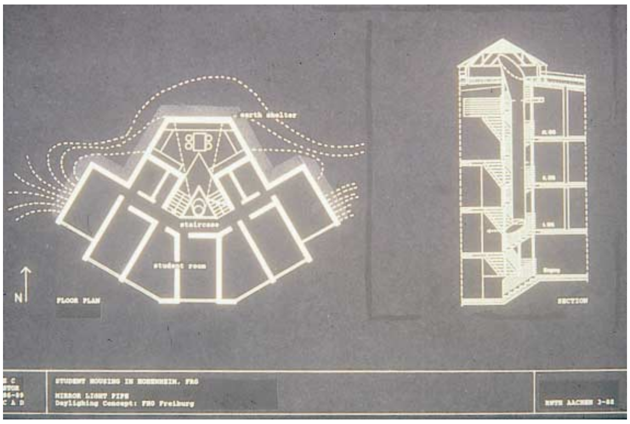


Fig. 22 (top left). Le Corbusier—Buildings in Chandigar (India). Fig. 23 (top right). Le Corbusier—The Tower of Shadows (maquette). Fig. 25 (above). R. Serra—Sport Centre in Barcelona (section). Fig. 27 (right). Hohenheim (Germany)—H. Schmitges, Student housing.



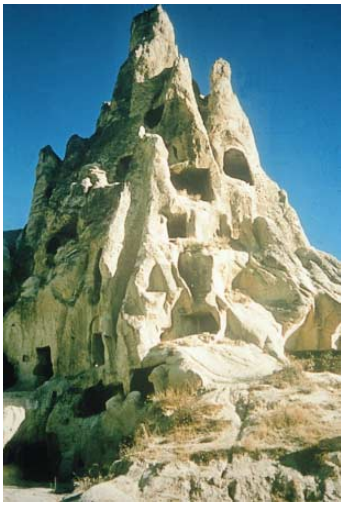


Fig. 28 (top left). Student housing: section. Fig. 29 (above left). Student housing: a yellow fluorescent truncated cone of the Fluorescent Planar Concentrators. Fig. 30 (above right). Cappadocia (Turkey): underground dwellings. Fig. 32 (left). Building for exhibition space (architect Gallo–Prof. Silvestrini): maquette.

Fig. 36. Mesa Verde (Colorado, U.S.A.): the Anasazi Indians settlement.

Fig. 37. Apulia (Italy): the Trullo.

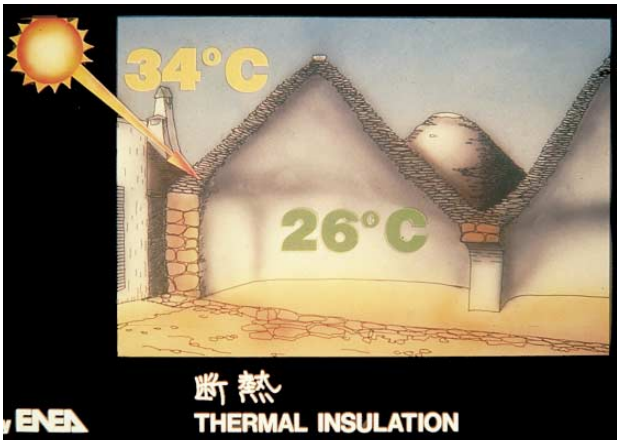


Fig. 38. Apulia (Italy): the Trullo.

Fig. 39 (top left). The Spanish Pavillon in Sevilla Expo '92 (Spain). Fig. 40 (top right). The Spanish Pavillon in Sevilla Expo '92 (Spain). Fig. 41 (middle). The Spanish Pavillon in Sevilla Expo '92 (Spain). Fig. 42 (above). The Maharaja Palace in Amber (India).

Fig. 43. The Maharaja Palace in Amber (India).

Fig. 44. Lahöre (Pakistan): the tents in the open space of the Mosque.

Fig. 45. Lahöre (Pakistan): the tents in the open space of the Mosque.

Fig. 46. The Holy Mosque of Medina.

Fig. 47. The Holy Mosque of Medina.

Fig. 48. The Holy Mosque of Medina.

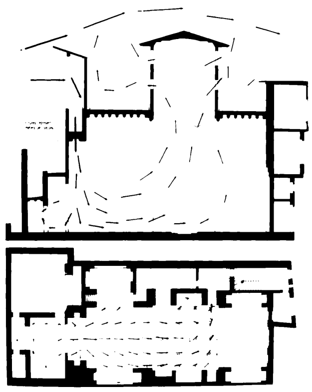


Fig. 10. House of the Muhibb Al-Din Muwaggi, survey showing air movements through the building (measurements were made by scholars from the Architectural Association School of Architecture in London, in 1973).

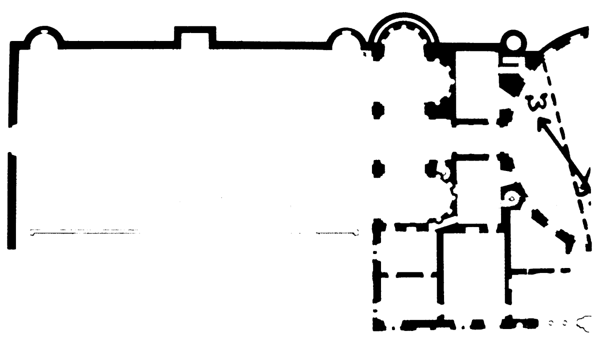


Fig. 18. Villa Madama of Raphael, Rome, Italy.

firm: differences of temperature of the air entry and exit points have even reached 20°C.

3. The sun

The knowledge of the course of the sun during the day and the seasons is another essential element of the architect's background information: solar charts show the sun direction at any time of the day for each latitude, by having a diagram that enables us to easily locate the position of the sun in a given place at a given time. By consulting these charts, one can determine what methods to use to keep the windows shielded at all times. First of all, it is best to give all windows a northern or southern

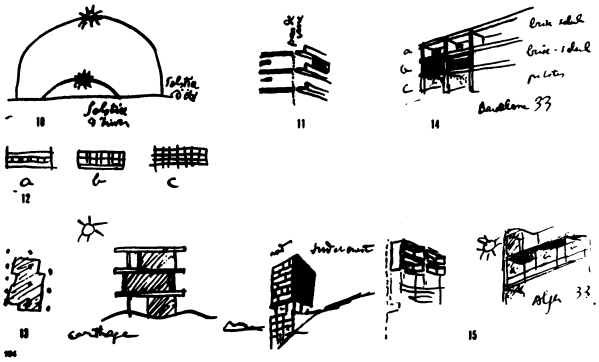


Fig. 19. Le Corbusier—Studies for the ‘brise-soleil’.

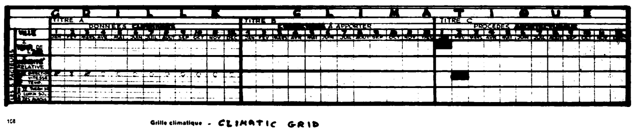


Fig. 24. Le Corbusier—The climatic grid.

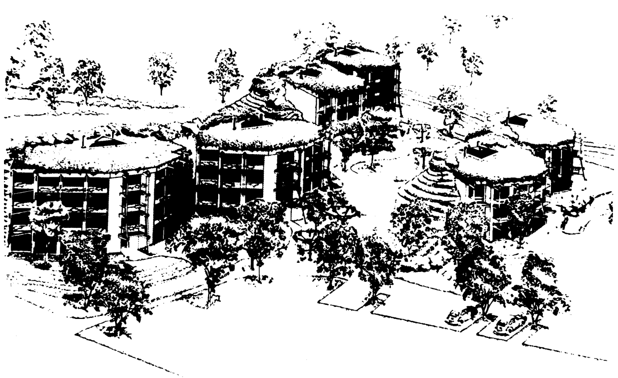


Fig. 26. Hohenheim (Germany)—H. Schmitges, Student housing.

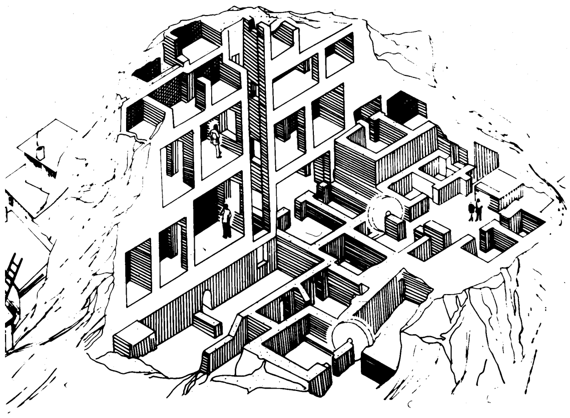


Fig. 31. Cappadocia (Turkey): underground dwellings (section).

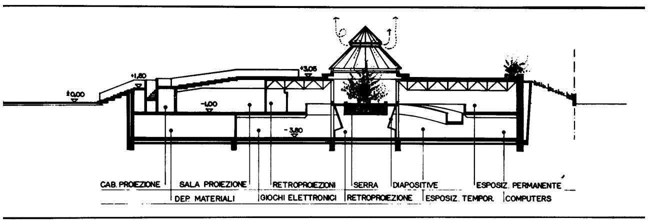


Fig. 33. Building for exhibition space (architect Gallo–Prof. Silvestrini): maquette.

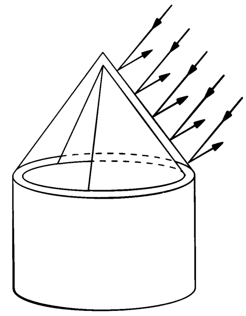


Fig. 34. The Silvestrini bell: performance in summer.

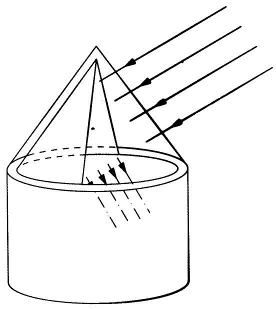


Fig. 35. The Silvestrini bell: performance in winter.

exposure; it is relatively easy to shield glass facing in these two directions because the sun here is always high in the sky. The situation is different to the east and the west, where the sun is low on the horizon and can penetrate deeply into the rooms. After the windows have been properly oriented, the next step is to set them back in order to keep them shaded at all times. Screening used as an energy conservation device during winter time can generally be used also as a screen against undesired solar radiation in summer time. There are many interesting screening solutions: more or less technologically sophisticated venetian blinds, double glass windows with a gas or small polyurethane pallets in the cavity, several types of membranes applied to the glass surfaces in order to modify its optical properties, spectrum selective windows, electrochromatic appliances etc.

An interesting solution is represented by a type of venetian blind placed between two layers of glass, operable from the interior of the building. The blades are covered on one side by a dark insulating material, and are silver-colored on the other side. This solution presents the widest choice of combinations: all open, intermediate position, silver screening on the outside (summer time), silver screening on the inside (night-time in winter), etc. There is also an ingenious proposal for an automatic screening system. It, too, is a kind of venetian blind with silver colored blades of larger dimensions. The movement of the blades is controlled by two small communicating containers filled with freon gas. In the summer, the containers are placed so that the solar radiation, by hitting the external one causes the expansion of the gas, making it flow inside the interior container. In this way the added weight makes the blind close. In winter, the position of the containers is inverted, so that the blades open during the day and close at sunset. There are also several types of membranes to be applied to the glass surfaces in order to modify its optical properties. Of particular merit among these is the 'heat reflector', a very thin metallic membrane with the characteristics of an extreme transparency to solar radiation and a high capacity for reflecting infrareds.

In the best solutions these elements become architectural plastic elements: the 'brise-soleil' is an important term of Le Corbuisier's architectural vocabulary, in Geneve,

in Barcellona, in Algier, to control... "the conditions of the exposure to the sun"—he writes—"the beneficiary entry of the sun in winter and the catastrophic entry of the sun in summer time...." [4].

During the winter solstice, the sun is low on the horizon, and its rays are welcome in the dwelling where they warm it physically as well as psychologically. The in-between seasons, spring and autumn, gratify the human being with a mellow sun, but the summer solstice and the heat-wave, with its intolerable temperature, transform our friend, the sun, into a pityless enemy.

> "In the Clarté building in Geneve... we have been instinctively enticed by jobs which bring us closer to the *Brise Soleil*" [5].

Le Corbusier stated:

> "I design the floors and they extended themselves beyond the glass panel with a balcony one and a half meters deep, with a parapet. Sliding shutters were added in front of the parapets because of the summer heat, thereby casting a first shadow and establishing a very satisfactory condition of sun penetration in winter (the sun being low over the horizon) and of sun barrier in the summer (when the sun is high)" [6].

In the Tower of Shadows in Chandigar (India), the sun is an architectural tool. The tower of shadows is placed on the edge of the Capitol, between the Hall of Justice and the Parliament. It is a tall and shady open hall. Its dark atmosphere invites meditation. The orientation of the building is north-south, making a deliberate break with the symmetry of the huge esplanade, the northern side is completely open, while the other three sides are equipped with brise-soleil. The course of the sun during all seasons has been very carefully studied and annotated at the Atelier Le Corbusier in order to determine the location and orientation of the various brise-soleil.

In fact, when looking at the model built expressly for the observation of the effects of the sun light with the alternation of the seasons, we can clearly see how the southern elevation is always in shade during the hottest periods, while being hit by the sun that penetrates the rooms in winter. The shadow pattern can be photographed on the model, but can also be computed from geometrical considerations. The relative methodology is fully developed: the following diagrams can be used for a graphic rendering of the shadow pattern. This is clearly a space designed to induce a sense of freshness, coolness in its interior during the hot Indian days, and to become, thanks to the physiological comfort experienced by the visitor, a place of encounter, reflection, meditation. But the sun, the great determinant of the design of the facade, is also an instrument of light and shadow, therefore of Architecture.

The Climatic Grid elaborated at the Master's Atelier in Rue de Sevres in Paris at the beginning of the 20th century, is still today a correct methodological approach for architectural design. The Grid is a visual tool for a correct design approach: it allows us to enumerate, coordinate, and analyze all climatic data of a specific place with the purpose of orienting, directing, and guiding the design process towards solutions in accord with human biology. All the excesses of an extreme climatic

condition should be regularized, and specified so as to provide, through an architectural solution, the necessary conditions for comfort.

3.1. *Setting up the Grid*

There are four horizontal divisions supplying the data for the environmental conditions. (The vertical divisions scan the time sequence). They are divided into three subsequent compartments:

(A) Conditions of the environment
(B) Corrections according to comfort
(C) Architectural solutions

3.1.1. *Conditions of the environment*

Also a representation of the environment considered. Every climate could be usefully represented by four basic elements:

(a) Temperature
(b) Air humidity
(c) Air movements (wind or currents, droughts)
(d) Thermal radiation of the objects under consideration.

The four horizontal sections of the Grid visualize the variations of the four factors mentioned above, during the lapse of time considered (day, year, etc.). The time is expressed by the vertical divisions according to the unit chosen: moments, days, seasons, years, etc., in the typical points such as, solstices, equinoxes, monsoon, etc. A red line indicates the annual range of the temperature. A blue hard line indicates the hygrometric curvature of the air on the second sector. The third sector shows the various directions and intensities of the winds throughout the year. Finally, the fourth sector supplies the thermal radiation of the walls and roofs of the design under consideration. In this way, all the conditions of the environment are graphically represented. The conditions of the environment constitute the first panel of the Grid.

3.1.2. *Corrections according to comfort*

The necessary corrections and biological modifications to ensure proper comfort are listed on the chart. The reading of the first sector has revealed the critical conditions under which man suffers. The second sector of the Grid follows the first one, and has the same horizontal and vertical divisions. The physician–biologist then inserts in some of those compartments the opportune modifications or corrections. Consequently, the reading of the second panel of the Grid will already represent, in essence, the program at the basis of the architectural design.

3.1.3. *The architectural solution*

The third sector of the Grid follows the second one, and has the same divisions of the previous two. A stamped seal, in each square compartment, corresponding to those

of panel 2, in which the changes and corrections of biological nature were shown, indicates the existence of a special plate, with the appropriate architectural solution. The stamp also shows a 'D' meaning that at this point of the grid there is a design. Two white squares under the 'D' enclose the point of reference that enables us to relate the document in question to its exact location in the 3rd sector of the Grid, and also to the date of its execution.

These graphic documents represent the architect's solution to the problem. A fairly easy manual operation can make section 3 of the Grid an extremely efficient tool; inside the summentioned squares, in the space left empty by the stamp 'D', a schematic plan of the drawing corresponding to it should be drawn. Thanks to this graphic visualization, the use of the Grid will be simplified [7].

To give physiological comfort means to create in rooms a high quality of life: the right temperature, no noise, good lighting. This is the purpose of the research on the best utilisation of daylighting (certainly to limit artificial lighting is also a good energy saving).

Of interest in this field is the research on light pipes to bring day-lighting in underground or internal rooms of the building, that normally utilize only artificial light: the light pipes are horizontal or vertical ducts, with highly reflective walls which transmit light from the external surfaces to the inside of buildings.

In the Sport Centre in Barcelona designed by Rafael Serra, the internal zones of this three-story building are lit by natural light provided by 'sun-ducts'. These are vertical ducts, with specular walls, one or two storeys high. Sunlight penetrates into them through 'sun-catchers' placed on the roof, and is reflected downward, until it reaches the areas to be illuminated.

In the student housing in Hohenheim (Germany, design: H. Schmitges; built in 1985) each of the six four-storey buildings has a glass pyramid on top of the staircase, providing light to the kitchen/dining rooms. Two components are used: 'light-pipes' and Fluorescent Planar Concentrators (FPC). Light-pipes are triangular vertical wells, with high reflectance (0.95) mirror walls, aimed at increasing the amount of daylight into the first-floor dining rooms. FPCs collect light in a yellow fluorescent truncated cone; the light is then guided down, within the 0.6 cm thickness of a 30 cm diameter transparent pipe, and is reflected by a mirror into the kitchen.

The quality of the working environment would be greatly improved by letting natural light reach and affect as much of the floor area as possible. Basically the problem can be stated as follows: how to effectively and economically bring natural light to those parts of large commercial buildings that are located far from the external envelope, where daylight is available, without causing discomfort.

First of all, it is important to obtain an optimal diffusion of the sunlight in the rooms: two interesting steps in this research are the prismatic surfaces and holographic films. The prismatic surfaces increase the sensitivity of the transmission factor to the angle of incidence, so that it is possible to reflect direct sunlight and transmit and re-direct skylight, as a function of the angle of the sun. Holographic films intercept sunlight and diffract it in another direction. Although under clear sky conditions a large amount of light is offered for day-lighting, it is often necessary to switch on the artificial light when shading devices are closed. By lightguiding building components

with holograms this unsatisfactory situation can be improved, directing the solar radiation to the ceiling, from where it is distributed evenly to the working level without glare effects. By means of vertical and horizontal adjustment of the direct radiation, room illumination can be achieved by comparatively small, clear window areas. Since the thermal resistance of glass is smaller than that of the opaque walls, this helps to minimize thermal losses while ensuring adequate internal lighting. To obtain a still more energy-wise result the use of solar energy should be coupled with a reduction of heat losses, essentially by insulating the walls and the windows. The extreme step in the direction were the underground dwellings; today we have testimony in many sites of the world characterised by border line weather conditions: Matmata in Tunisia, Cappadocia in Turkey, Honnan in China.

Sometimes a physics principle—the low heat dissipation of the cylindrical shape—can inspire the basic idea of an architecture.

In this building project of exhibition space (design: architect C. Gallo with Prof. V. Silvestrini) the shape and the siting of the building were studied so as to minimize thermal losses. The cylindrical shape, the partial earth coverage and the admission of light through a central conical light well reduce heat losses to very low values, even though the constructional solutions that have been chosen are not exaggerated in terms of thermal insulation (the heat conduction coefficient assumed for the outer walls is 1.5 W $m^{2\circ}C$). Under these conditions, heat loss is dominated by the contributions due to ventilation. The unconventional skylight (the Silvestrini bell) was designed to optimize the collection of solar energy. Inside the conical glass cover, there is a rotary segment; its inner surface is white, so as to reflect solar radiation toward the inside of the building (the winter garden). This central structure, which provides for the natural lighting of the whole building, results in very low heat loss because of its geometry. On sunny winter days, it receives an amount of solar radiation comparable with the overall energy requirements of the building. During the summer, the same conical segment that reflects light inside during the winter is rotated so as to shade the winter garden. The air conditioning load is thus reduced essentially to that necessary to remove excess humidity from the new air brought into the building by ventilation.

The scientist Vittorio Silvestrini writes about the ‘round house’ of Mario Botta:

> “Mario Botta is not an expert in solar energy: he is simply an architect. But like all good architects, he must take into account the problem of comfort and consequently of a rational use of energy in the projects he designs. In his projects for private houses there is a recurring characteristic pertinent to the question of energy, and that is the fact this his houses are ‘introverted’ so to speak. The external shell is particularly compact and closed: the forms, cylindric and cubic, reduce to a minimum the dispersion of energy, and windows are also kept to a minimum. These forms both correspond to a requirement of energy conservation, that of reducing thermal dispersion and to a perfectly architectonic need, that of offering a controlled view of the surroundings. The source of light and heat is a central nucleus which we could call the ‘energy heart’ of the house. This nucleus generally receives

> energy by means of a skylight placed on top of the building. Botta's houses also make use of a temperate micro-climate, but this climate is realized in an internal rather than external space. The advantages are evident. The external shell can now be extremely well insulated, there is no obligatory orientation, climate control is simple even during the summer, and costs are moderate. The houses of Mario Botta are real homes, not mere accidents of experimental technology" [8].

The Master of contemporary architecture, Louis Kahn, observes about his Management Training School at Ahmedabad in India:

> "The orientation of the houses follows the direction of the winds; all the walls are parallel to this direction. The walls are traced diagonally around a court in order to define it, while keeping the regularity demanded by the layout . . . it will be noticed that I have inserted a light well in the school building. I believe that, in a certain way, this device is superior to the one I had invented in Luanda. There I had built a wall to screen the sun and to modify its reverberation, while here the solution has become an integral part of the composition . . . This could be called an inside-out bow window" [9].

In the houses of Ghardaia, Algeria, the light well is formed by the 'chebeq', a square hole in the ceiling that makes up for the total absence of windows and provides air-conditioning as well as light. The indoor is cooled by the air flow created between the chebeq and a number of openings in the walls beneath. In this climate zone, known as 'the desert within the desert', the houses are built adjacent to each other, with thick stone walls, so that the living quarters are shaded. The stone slows heat penetration during the day and releases the heat during the night.

4. Thermal mass

In the past, the thermal mass of walls was always an element to minimize temperature oscillations and to protect the rooms from the external heat or cold.

> "The Indian settlement of Mesa Verde (ca 1200) in Colorado represents a perfect example of exploitation of natural resources for survival. The settlement is located in a horizontal cut of the rock with a southern exposure, sheltered from the summer sun, but not from the winter one. The immense rock that the Indian settlement leans against provides a very large mass of thermal inertia, thereby guaranteeing a nearly constant comfort level throughout the year" [10].

In Mesa Verde the combination cave/buildings provide a kind of energy collector that is over 50% more efficient in the winter than in the summer. In winter, the sun rays—because of the lower angle of incidence—have free access to the cavity in the rock. The heat from the solar radiations, well absorbed by the rock itself and by the

adobe of the buildings, is slowly released to the environment after sunset, thereby providing a constantly comfortable microclimate (as compared to the extremely cold winters and hot and dry summers). The daily life of the Anasazi Indians took place at the interior of the 'kiva', a covered circular space, heated by a central open fireplace. A natural ventilation system provided the air change. The hot air heated by the fire went out from a hole in the roof, while a cold air inlet at the floor level provided cold air that was deflected by a low wall in front of the fireplace, forcing its circulation around the 'kiwa'.

Two other interesting examples of 'spontaneous' bioclimatic architecture in Italy are 'dammuso' and 'trullo'. Both buildings feature very thick walls and minimal openings, allowing for a comfortable microclimate inside. Dammuso, the typical dwelling of the island of Pantelleria, represents an example of spontaneous architecture of bio-climatic inspiration. The climate of the island presents a high temperature, ranging from 34°C in August to 10°C in January. There are low levels of rainfall and strong winds, and consequently the main purpose of the Dammuso is to provide protection from the summer heat and the winds. There are several thousand Dammusi in the island of Pantelleria. This type of dwelling evolved many centuries ago as a response to the need for a temporary shelter for vineyard workers and a tool shed and storage for produce. The roof of the Dammuso is made by a barrel vault externally waterproofed, and shaped to collect rainwater to be stored in an underground cistern. There is only one door to the dwelling and no windows to speak of, except two or three small openings in the walls for the sole purpose of ventilation. The walls of the original Dammuso vary in thickness between 80 cm and 2 m. They are made by an outer and inner wall of large dry-set stones and the central cavity is filled with smaller stones. This construction provides such a good insulation from the exterior that, during the past two centuries (once the danger from outside invasions had ceased) they have become the permanent residence of the islanders. Measurements taken on the interior of a typical Dammuso during the month of August, show a fairly constant temperature of 26°C, during both night and day.

The hot climate of Apulia calls for climatization. The traditional answer to that has been the Trullo, a stone shelter whose large masonry walls mass act as some sort of thermal regulator, by absorbing the radiation heat during the day and releasing it slowly at night, thereby levelling the temperature variations, and making the interior temperature several degrees lower than the exterior one during the day time. The internal thermal behaviour of the Trullo has been verified by a comparison of the results of a simulated test, using a thermal grid code developed by the Laboratorio Progettazione Ambientale (Environmental Design Laboratory), and the results of a weekly temperature survey done during the summer. The simulated data and the collected ones correspond, and show that there is an internal thermal variation of 4°C in correspondence of an external variation of 10°C.

Thus we examined various ways to create passive cooling in architecture: to reduce heating, to cool the hot air by other cold air, water or earth . . .

Another aspect of the problem is open public spaces in hot countries.

5. Open public spaces

5.1. *Vegetation*

Vegetation around a building is important: this means choosing a site rich in greenery or else creating vegetation where there was none. The role of the micro-climate, and of its possible breezes and currents is fundamental in determining the conditions for well being in a built environment. Besides creating shade, vegetation transpires water and thus provokes natural cooling through evaporation. A recently published review [11] quotes reductions of temperature through evaporation of 2–3°C. It seems well demonstrated that joint evaporation and transpiration of a single tree can save from 1–24 MJ of electricity in terms of air conditioning per year; a lawn can cool a sunny lot by 6–8°C, while the evaporation of a hectare of grass corresponds to more than 125 MJ per day.

In one of its works [12], the Rocky Mountain Institute compares the reduction of the thermal load due to vegetation in three cities: Sacramento (34%), Phoenix (18%, dry climate), Los Angeles (44%). This data seems to indicate that vegetation works more effectively in a damp climate, where it can, however, lead to a rise of humidity.

In dry climates vegetation can influence the dry bulb temperature. In the many bioclimatic systems realised in Bioclimatic Rotunda in Sevilla Expo '92 by Spanish architects, very effective coolers in a hot and dry climate, the vegetation is essential: in the plan the proportion between green and buildings is 60/40. The vegetation refreshing effect consists of temperature mitigation, solar radiation's reduction, relative humidity increasing, wind mitigation and direction (regulation). The main difference between refreshing effects from vegetation and from structures built by man is that an inorganic material has a limited refreshing capacity, based on thermal characteristics of the materials; a plant on the contrary is a living organism that will regulate its branches and leaves to utilise most of the solar radiation.

In Sevilla, other key-concepts of passive cooling are utilised. Besides the ventilation, the utilisation of earth mass, there are water jets, fountains, water films and water floors: water runs beneath pavements made of porous material that allows water to evaporate. Micronizers increase the evaporation during the hottest period, and running water and cold air coming from underground pipes give their contribution to thermal well-being.

Running water, together with a cold air current, is the cooling system that was utilised in the Maharaja Palace of Amber, near Jaipur, built in the 16th century: a room with one side entirely open towards the courtyard is cooled by a waterway crossing it, bounded by two stone sides which are pierced to admit air.

6. Shading devices

In Bioclimatic Rotunda in Sevilla Expo, a focal point is the generation of shadows on public spaces: but it is important that these sun protective systems are movable

and they can be removed during the night to make possible the heat dissipation by long wave-length radiation to the sky.

The same system is utilised for example in the open space of oriental mosques: the big tent for solar protection during the day are removed at the evening. In the Holy Mosque of Medina, twelve umbrellas with a diagonal span of 24 m, installed in groups of six, immediately answered any doubts one might have had as to the possibility of solving the climatic problem of Middle-Eastern historic buildings without incurring a heavy environmental impact. The twelve shading mechanisms are the invention of the Bodo Rasch Jr, the natural successor of Frei Otto, inventor of the tensile structure, as a technologically advanced lightweight system of coverage. The extension and retraction of the membranes is regulated by a computerized system in which local climatic data have been recorded in conjunction with the spatial configuration of the Mosque and its courtyards, so that efficient functioning is guaranteed in all atmospheric conditions. Generally speaking, the principle adopted prescribes opening the membrane cover during the day in summer as protection from the strong sunlight that raises the temperature to 45°C in the shade, while its closure at night permits the evacuation of heat absorbed during the day by the thick walls. In winter, the procedure is reversed, so that the umbrellas are closed during the day, allowing the mild sun to warm the marble paving and walls, whose thermal inertia is preserved at night by opening up the membrane to prevent extreme cooling. Lastly, the convertible structures are equipped with a windspeed monitor which automatically prevents opening and closing operations when speeds exceed 36 km/h. Each umbrella has four lamps integrated into the claddings above the column capital to illuminate the courts at night, and air outlets located in the base and capital of the lower column which are linked to the building's air-conditioning system.

References

[1] Ph. Foster-Raphael on the Villa Madama: the test of a last letter ('Sonderheft aus dem Romischem Jahrbuch fur Kunstgeschichte', XI, 1967–68).
[2] Fathy Hassan. Natural Energy and Vernacular Architecture. Chicago, 1986.
[3] Proceedings of World Solar Summit, UNESCO, Paris 1993: Solar Energy in Architecture.
[4] Le Corbusier. Oeuvre complète. Artemis, Zurich, 1970.
[5] Idem.
[6] Idem.
[7] Idem.
[8] A.A.V.V. Bioclimatic Architecture. Leonardo De Luca, Rome, 1992.
[9] Idem.
[10] Crowler RL. AIA—Solar Group Architects, Sun earth. How to apply free energy sources to our homes and buildings. Denver, Colorado: A.B. Hirscenfeld Press inc., 1976.
[11] C.E. Building 2000. Den Ouden C, Steemers T. Kluwer Academic Publishers, 1992.
[12] Rocky Mountain Institute: The State of the Art: Space cooling, 1986.